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GAS-PHASE CONTROLLED MASS TRANSFER OF PACKED COLUMNS CORRELATED TO THE LOADING POINT

by

R. LOPES CARDOZO

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In combination with the loading-point correlation of GARNER, which was verified experimentally,

$$\left(\frac{G_{\text{loading}}}{3600\rho_G}\right)^2 \frac{S}{g} = \epsilon f \left(\frac{L}{G}\right)_{\text{loading}}$$

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the efficiency of packed columns can be calculated with :

$$\left(\frac{H_G S}{\varepsilon}\right) = [(Sc)^{0.5}(Re')^{a}] \times [(\Lambda)^{b} f(We')] \times \left[\left(\frac{D}{D_p}\right)^{c}\left(\frac{\mathscr{L}}{D_p}\right)^{d}\right] \quad (15)$$

mass-transfer group = gas group × liquid group × column dimensions group

This equation, valid for gas-phase controlled mass transfer, has the following numerical values of the exponents :

Packing	*a*	*b*	*c*	*d*
Raschig-rings	0.44	—0.39	0.65	0.195
Berl-saddles	0.77	—0.45	0.28	0.195

The introduction of a modified Weber-Froude number (We') follows from the consideration that the dispersion of the absorption liquid is, apart from being a function of the amount of liquid, also a function of its physical properties. The dependency on We' is given in a graphical form.

The standard deviation of the experimental H_G-values ranges from 7 to 30 per cent for the various packings and packing sizes.

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Gas-phase controlled mass transfer of packed columns correlated to the loading point

R. LOPES CARDOZO

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Abstract—During a study of the performance of a packed column for the absorption of gaseous iodine it was found that the results could be correlated with the help of a loading number Λ. This number is defined by

$$\Lambda = \frac{\text{the actual liquid flow rate}}{\text{the calculated liquid flow rate at the loading point}} \tag{11}$$

In combination with the loading-point correlation of GARNER, which was verified experimentally,

$$\left(\frac{G_{\text{loading}}}{3600\rho_G}\right)^2 \frac{S}{g} = \varepsilon f \left(\frac{L}{G}\right)_{\text{loading}}$$

the efficiency of packed columns can be calculated with:

$$\left(\frac{H_G S}{\varepsilon}\right) = [(\text{Sc})^{0.5}(\text{Re}')^a] \times [(\Lambda)^b f(\text{We}')] \times \left[\left(\frac{D}{D_p}\right)^c \left(\frac{\mathscr{L}}{D_p}\right)^d\right] \tag{15}$$

mass-transfer group = gas group × liquid group × column dimensions group

This equation, valid for gas-phase controlled mass transfer, has the following numerical values of the exponents:

Packing	*a*	*b*	*c*	*d*
Raschig-rings	0·44	−0·39	0·65	0·195
Berl-saddles	0·77	−0·45	0·28	0·195

The introduction of a modified Weber–Froude number (We′) follows from the consideration that the dispersion of the absorption liquid is, apart from being a function of the amount of liquid, also a function of its physical properties. The dependency on We′ is given in a graphical form.

The standard deviation of the experimental H_G-values ranges from 7 to 30 per cent for the various packings and packing sizes.

1. INTRODUCTION

IN NUCLEAR industry it is often necessary to remove gaseous iodine from air. Many possibilities are available such as silver-coated materials (SILVERMAN [1]), activated charcoal filters (e.g. LOPES CARDOZO and DEJONGHE [2]), all kinds of wet contacting devices etc. Each method has its own merits and a choice should be made according to the problem given.

The efficiency of a wet packed column for the removal of radioactive gaseous iodine from air was studied with the help of a 12-in. dia. column, packed to a height of about 6 ft with $\frac{3}{4}$-in. ceramic Raschig-rings. The absorption liquid was 5 (weight) per cent sodium hydroxide used in recycle. In order to keep entrainment as small as possible the column worked mostly below the loading point.

2. EXPERIMENTAL

2.1. *Operating procedures*

The absorption column (Fig. 1) had the following specifications:

1. inside diameter	0·3 m.
2. packing height	1·94 m.
3. packing	20 × 20 × 2·2 mm ceramic Raschig-rings, porosity 0·73, maximum wettable surface 235 m^2/m^3.

4. support plates — weir type.
5. liquid distributors — weir flow type with 4 feed points.
6. entrainment separator — 0·3 m rings above liquid inlet.

he induced draught fan had a maximum capacity of 350 m³/hr. The absorption liquid consisted of 5 (weight) er cent sodium hydroxide in water and was continuously cycled.

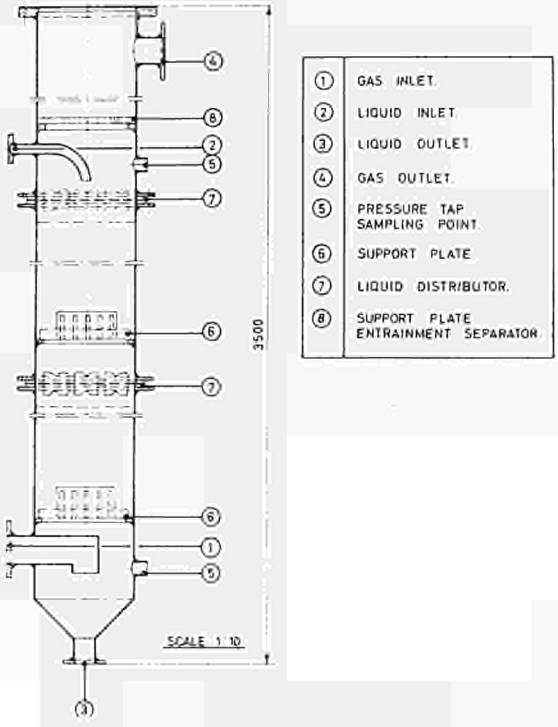


FIG. 1. 12-in. diameter packed column.

The gas stream was made up by mixing a small air stream containing gaseous iodine, spiked with iodine 131, with the main stream, the latter being normal unfiltered air.

The inlet and outlet concentrations of the iodine were measured in samples taken at the sampling points, by absorption through a train of sodium hydroxide wash bottles. The activity was counted in the liquid phase with a scintillation counter and since the specific activity of the iodine was known, the concentrations could be calculated from the activity of the samples.

2.2. *Pressure drop, loading and flooding of the column*

Fig. 2 represents the pressure drop, as measured between liquid inlet and gas inlet, as a function of

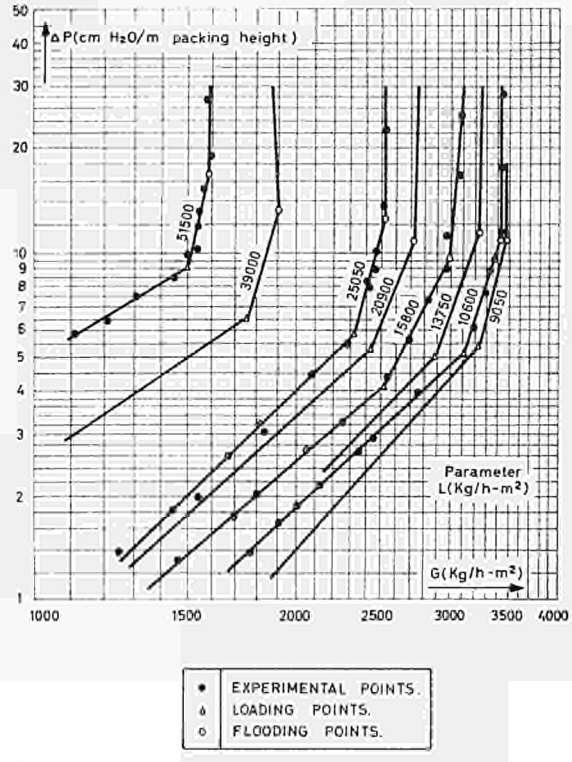


FIG. 2. Pressure drop, loading and flooding of the 12-in. diameter Raschig-ring column for the air–water system.

gas and liquid flow rates for the air/water system.

The pressure drop below loading could be correlated according to LEVA [3]:

$$\Delta P = \frac{\alpha 10^{\beta L}}{\rho_G} G^2 \qquad (1)$$

with $\alpha = 3{\cdot}3 \times 10^{-7}$ instead of $5{\cdot}77 \times 10^{-7}$ and $\beta = 2{\cdot}4 \times 10^{-5}$ instead of $1{\cdot}48 \times 10^{-5}$. The differences can possibly be attributed to variations in the design of support plates etc. It is noted that the introduction of the gas density in LEVA's correlation seems to have been done more to account for temperature and pressure variations than to account for various gases that were tested.

The pressure-drop curves show two distinct break points. The upper one representing the flooding point and the lower one marking the beginning of the loading zone. This point is called here the loading point. It was found that the lower break points coincide very well with a loading velocity

correlation for Raschig-rings, given by GARNER *et al.* [4]:

$$\left(\frac{G_{\text{loading}}}{3600\,\rho_G}\right)^2 \frac{S}{g\varepsilon} = f\left(\frac{L}{G}\right)_{\text{loading}} \qquad (2)$$

The results obtained with the ¾-in. rings, together with other reported data, are shown in Fig. 3. The average deviation is about 8 per cent. The loading line is in fair agreement with the correlation of OTAKA and KIMURA [7], but since no "trial and error" operation is involved with the use of GARNER's relation, the latter is preferable.

Loading data for Berl-saddles are correspondingly correlated by GARNER *et al.* [4], the ordinate of Fig. 3 having a value of about 2·9 times the ordinate for Raschig-rings at equal L/G values.

The close agreement between experimental and reported loading data could not be found with the flooding data. Some reported flooding correlations are also given in Fig. 3. The correlation of LEVA [8] and the one of HOFFING and LOCKARD [9] are reshaped in order to obtain a homogeneous representation of all data. The experimental flooding data are a factor 1·5–2·5 lower in respect to the ordinate than would follow from the reported correlations. It is believed that the difference is caused by the design of the column.

It can thus be concluded that in order to find a fixed point in the working conditions of a packed column it is preferable to select the loading point rather than the flooding point. Equation (2), in combination with Fig. 3, can very well be used for the determination of the loading point of packed columns.

2.3. *The absorption of gaseous iodine*

The absorption of gaseous iodine in sodium hydroxide solutions is a chemical reaction, and mass transfer is completely gas-phase controlled (TAYLOR [10]).

The height of a gas-film transfer unit H_G equals the height of an over-all transfer unit H_{OG}:

$$H_{OG} = \frac{\mathscr{L}}{N_{OG}} = H_G \qquad (3)$$

The number of transfer units N_{OG} was calculated from the concentration of the iodine in the gas phase at the inlet and outlet of the column. These concentrations were very small, the logarithmic

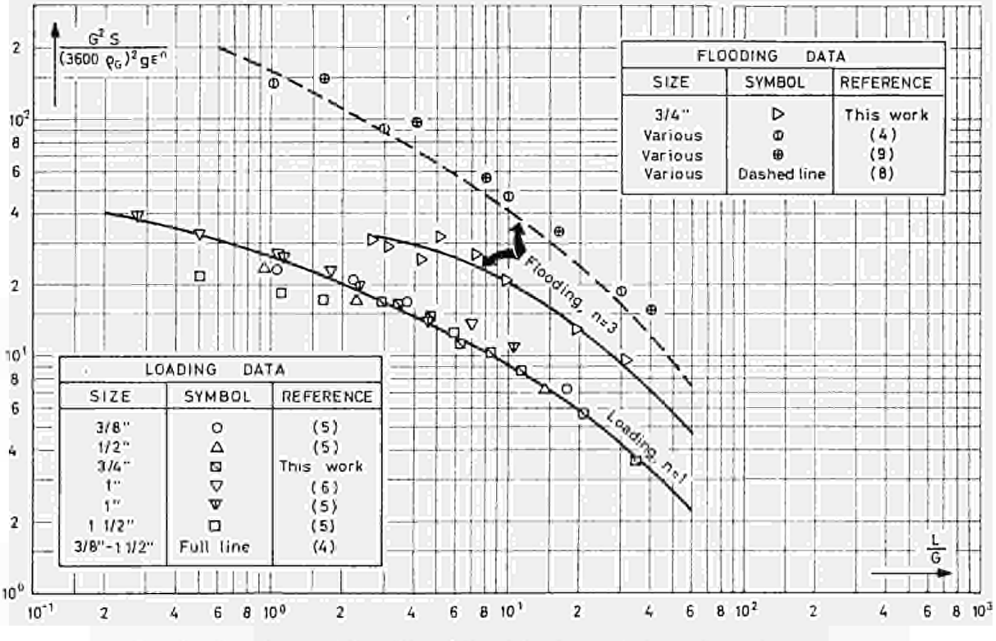


FIG. 3. Loading and flooding of Raschig-rings columns, air–water system.

mean $(\Delta y)_{lm}$ having a value around 10^{-3} mg/m^3, so that follows

$$N_{OG} = \int_e^0 \frac{dy}{y - y^*} = \int_e^0 \frac{dy}{y} = 2{\cdot}3 \log \frac{y_0}{y_e} \qquad (4)$$

The experimental data are given in Table 1, section 3.2.2.

3. CORRELATION OF H_G DATA

3.1. *Previous work*

Mass-transfer data are presented mostly including the influence of the liquid flow rate on the wetting of the packing. Also in the case of pure gas-phase controlled mass transfer, the liquid flow rate plays an important part. It is however not yet well established how the influence of the liquid flow rate can best be given. A variety of correlations on gas-phase controlled mass transfer can be found in literature.

WEISMAN and BONILLA [11] found that the effective wetted surface of the packing was a function of the gas and liquid flow rates, expressing the data of MCADAMS *et al.* [12] on the evaporation of water in a 1-in. carbon-rings column in the following way:

$$\frac{S_e}{S} = 0{\cdot}024 G^{0{\cdot}31} L^{0{\cdot}07} \qquad (5)$$

The same method applied to the data of YOSHIDA and TANAKA [13] for 1-in. ceramic rings for the same system, leads to the result

$$\frac{S_e}{S} = 0{\cdot}0095 G^{0{\cdot}41} L^{0{\cdot}20} \qquad (6)$$

A more general relation for gas-phase controlled absorption is given by PRATT [14],

$$\left(\frac{K_G P M \varepsilon}{G}\right) = 0{\cdot}123 (\mathrm{Re}')^{-0{\cdot}25} (\mathrm{Sc})^{-2/3} w \qquad (7)$$

Equation (7) in this form is valid for Raschig-rings only. The influence of the liquid flow rate is incorporated in the factor "w", depending on the actual liquid flow rate as compared to the so-called minimum effective wetting rate.

A similar correlation, but without the wetting correction and an exponent of the modified Reynolds number Re′ of $(-0{\cdot}36)$ is given by SHULMAN and MARGULIS [15].

Another possibility is to correlate the influence of the liquid flow rate to the relative velocity of both phases $\bar{v}$ and to the wetting rate Γ. This is done by TAYLOR [10] who examined the absorption of gaseous iodine in a wetted-wall column. For the gas-phase controlled absorption at 20°C he obtained

$$k_G = \gamma \bar{v}^m \Gamma^{0{\cdot}07} \qquad (8)$$

with $\gamma = 480$ and $m = 0{\cdot}45$ at $\bar{v} < 1{\cdot}1$ m/sec and $m = 0{\cdot}67$ at $\bar{v} > 1{\cdot}1$ m/sec.

MORRIS and JACKSON [16] correlate the influence of the liquid flow rate only to the relative velocity by introducing a factor $(\bar{v})^{0{\cdot}75}$.

A completely different approach is given by CORNELL *et al.* [17]:

$$H_G = \frac{\psi (\mathrm{Sc})^{0{\cdot}5}}{f} \left(\frac{D}{0{\cdot}3}\right)^{1{\cdot}24} \left(\frac{\mathscr{L}}{3{\cdot}05}\right)^{1/3} \qquad (9)$$

This relation, valid for Raschig-rings, incorporates the liquid flow rate in two factors, namely "f", depending on the liquid hold-up and "Ψ", the flood factor, a function of the per cent flood:

$$\% \text{ flood} = \left(\frac{100G}{G_{\text{flooding}}}\right) \qquad (10)$$

It is difficult to decide which of the above-mentioned correlations is the best and most universal one. However, it seems quite certain that the influence of the wetted surface on mass transfer is very important. It is believed that the wetted surface can be best related to the loading or flooding state of the column. Since it was shown that the loading point is a well defined and well known column condition and less depending on variations in column design, a gas-phase mass-transfer correlation, based upon this condition, will be developed hereafter.

3.2. *Correlation of H_G data based upon the loading state*

3.2.1. *Introduction.* It is believed that the following groups should be present in a general correlation for gas-phase controlled mass transfer:

(1.) A group representing the gas velocity and the gas physical properties. The gas velocity is given

in the modified Reynolds number, $D_P G/\eta\varepsilon$, with an exponent coming forth from the experimental data. D_p is the equivalent spherical diameter defined as the diameter of a sphere having the same volume as the solid part of a packing element.

The gas physical properties are given in the Schmidt number, $\eta/\rho_G\mathscr{D}$, with an exponent of $(-0{\cdot}5)$ according to LYNCH and WILKE [18]. The so-called gas group will thus be of the form

$$(\mathrm{Sc})^{0{\cdot}5}(\mathrm{Re}')^a$$

(2.) A group representing the liquid velocity and the liquid physical properties. These factors play an important part with regard to liquid dispersion over the packing surface, wall effect and hold-up, the latter being correlated by JESSER and ELGIN [19]. Since here only gas-phase controlled mass transfer is considered, the influence of the liquid properties, notably on the effective wetted packing surface S_e and on the void fraction ε, is of importance. The void fraction is supposed to remain constant, which is approximately true if the column works around or below the loading point.

Since it was possible to correlate a wide variety of loading data with a high degree of accuracy, it seems feasible to use this correlation to express the influence of the liquid flow rate on the wetted surface. There are two good reasons to do so. Firstly, it is generally accepted that the wetting is improved when approaching the loading zone, with, at the loading point, a maximum wetted surface; secondly, it is always found that optimum column performance, from the point of both efficiency and pressure drop, is obtained around the loading point.

Therefore, a loading number Λ is introduced and expressed by

$$\Lambda = \frac{\text{the actual liquid flow rate}}{\text{the calculated liquid flow rate at the loading point}} \qquad (11)$$

At liquid flow rates above the loading point, thus at $\Lambda > 1$, the matter becomes more complex and will only be treated shortly in section 3.2.4.

Besides the liquid flow rate, also the liquid physical properties affect the dispersion over the packing surface. In order to account for this, an irrigated packed column is compared with a mixing device. The factors governing the liquid dispersion are the velocity, viscosity, density and surface tension of the liquid and the packing shape and size. The surface tension, especially, can be important since it is readily understood that the ease of wetting of the packing surface and the stability of the once-formed wetted area are greatly dependent upon the surface tension of the absorption liquid.

Since it was shown by LANGLOIS [20] that liquid viscosity does not considerably affect the extent of the liquid area formed, the viscosity is omitted here. Dimension analysis shows that the dispersion is a function of

$$f\left(\frac{D_p\rho_L V_L^2}{\sigma}\right), \left(\frac{V_L^2}{D_p g}\right) = f(\mathrm{We}), (\mathrm{Fr}) \qquad (12)$$

The Weber number, $D_p\rho_L V_L{}^2/\sigma$, is a criterion for the facility with which the liquid is spread out over the packing surface, with a better dispersion at higher Weber-number values. The opposite is true for the Froude number, $V_L{}^2/D_p g$, which is proportional to the quantity of energy present in the liquid. Since the liquid velocity or the liquid flow rate will be incorporated in the loading number, it is possible to eliminate V_L from equation (12). In that case the exponents of We and Fr become equal, resulting in a modified Weber–Froude number,

$$\mathrm{We}' = \frac{D_p^2\rho_L g}{\sigma}$$

Combination of the two groups influencing the effective wetted packing surface S_e gives

$$S_e = Sf(\Lambda, \mathrm{We}') \qquad (13)$$

For the calculation of the loading point according to equation (2) the theoretical value of S should be taken, equalling the total outside area of a packing element multiplied by the number of elements per cm^3. The same value should be inserted in equation (13).

(3.) The column dimensions group incorporating the packing height and the internal column diameter, but also the way of introduction of the liquid. The column diameter is important since in columns of large diameter the liquid distribution is adversely affected, whilst in small columns the wall effect may play an important part. To improve liquid distribution, usually many feed points are designed. In this study four feed points were used, corres-

ponding to a value of 60–70 per m^2 column cross-section, a value recommended by manufacturers [21]. Most of the other data used for the evaluation of the general correlation were obtained with sixty or more feed points per m^2 or with a spray device as liquid distributor.

MURCH [22] investigated the influence of the column diameter and packing height upon the mass-transfer efficiency and recommends a correction factor of $(D^{1.24}\mathscr{L}^{1/3})$ for Raschig-rings fractionation columns. More open packings, such as rings made of protruded materials, have a better liquid distribution, hence an exponent of, for example, only (0·3) for the diameter correction. In this study other exponents will be found for the column dimensions group

$$\left(\frac{D}{D_p}\right)^e \left(\frac{\mathscr{L}}{D_p}\right)^d$$

valid for sixty or more feed points per m^2 of column cross-section.

(4.) The mass transfer group includes H_G, S and the void fraction ε : $H_e S/\varepsilon$.

The general correlation will have the following form:

$$\left(\frac{H_G S}{\varepsilon}\right) = [(\mathrm{Sc})^{0.5}(\mathrm{Re}')^a] \times [f(\Lambda, \mathrm{We}')] \times$$

mass-transfer group = gas group × liquid group ×

$$\times \left[\left(\frac{D}{D_p}\right)^c \left(\frac{\mathscr{L}}{D_p}\right)^d\right]$$

× column-dimensions group (14)

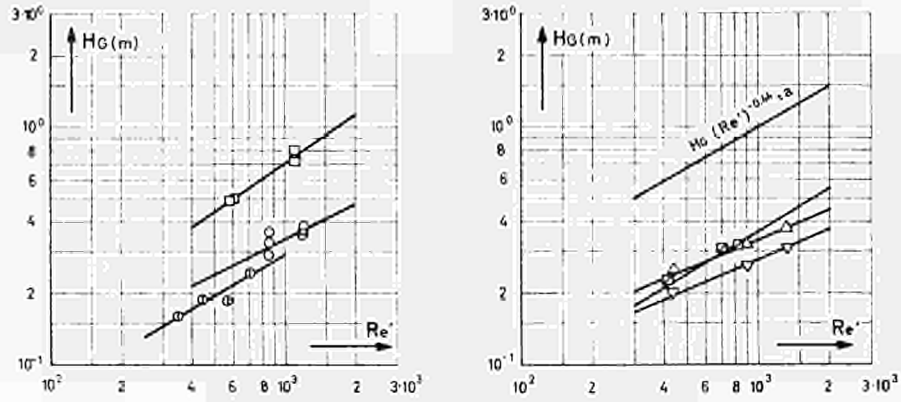
3.2.2. *Evaluation of the general correlation.* At first, the general correlation will be derived with water as absorption liquid. At the end other liquids will be incorporated with help of the modified Weber–Froude number.

Equation (14) is for the moment written as

$$\left(\frac{H_G S}{\varepsilon}\right)[(\mathrm{Sc})^{-0.5}(\mathrm{Re}')^{-a}][f(\Lambda)] = F\left[\left(\frac{D}{D_p}\right)^c \left(\frac{\mathscr{L}}{D_p}\right)^d\right] \quad (14a)$$

with $F = f(\mathrm{We}')$.

The experimental data, obtained with the ¾-in. Raschig-rings column, are given in Table 1. The absorption liquid resembles closely to water.



SYMBOL	SIZE	Λ	REFERENCE
Φ	15 mm	0.1	(13)
△	1"	0.19	(5)
▽	1"	0.28	(5)
□	1"	0.45	(6)
⊠	1/2"	0.47	(5)
○	3/4"	0.95	This work

FIG. 4. Evaluation of the Reynolds-number exponent for Raschig-rings.

Table 1. Experimental data on the absorption of gaseous iodine in a sodium hydroxide solution

Run	G (kg/hr/m²)	L (kg/hr/m²)	Re′	Λ	y_0 (mg/m³)	y_e (mg/m³)	H_G (m)	F Equation (15a)
1	1415	35,500	505	0·66	$0{\cdot}28 \times 10^{-2}$	$0{\cdot}36 \times 10^{-4}$	0·443	0·33
2	1415	35,500	505	0·66	$0{\cdot}81 \times 10^{-2}$	$1{\cdot}42 \times 10^{-4}$	0·483	0·36
3	1415	35,500	505	0·66	$1{\cdot}95 \times 10^{-2}$	$0{\cdot}915 \times 10^{-4}$	0·375	0·28
4	1415	35,500	505	0·66	$2{\cdot}65 \times 10^{-2}$	$1{\cdot}78 \times 10^{-4}$	0·392	0·29
5	1735	23,100	618	0·58	$0{\cdot}565 \times 10^{-2}$	$1{\cdot}29 \times 10^{-4}$	0·509	0·325
6	1735	23,100	618	0·58	$1{\cdot}23 \times 10^{-2}$	$1{\cdot}065 \times 10^{-4}$	0·411	0·265
7	1735	23,100	618	0·58	$1{\cdot}19 \times 10^{-2}$	$2{\cdot}60 \times 10^{-4}$	0·509	0·325
8	1735	23,100	618	0·58	$1{\cdot}46 \times 10^{-2}$	$1{\cdot}73 \times 10^{-4}$	0·440	0·28
9	1860	35,500	661	1	$2{\cdot}93 \times 10^{-2}$	$1{\cdot}38 \times 10^{-4}$	0·360	0·28
10	2160	14,800	770	1·8	$1{\cdot}24 \times 10^{-2}$	$0{\cdot}715 \times 10^{-4}$	0·378	0·27
11	2160	14,800	770	1·8	$0{\cdot}72 \times 10^{-2}$	$0{\cdot}755 \times 10^{-4}$	0·418	0·30
12	2160	14,800	770	1·8	$1{\cdot}24 \times 10^{-2}$	$0{\cdot}59 \times 10^{-4}$	0·365	0·265
13	2480	18,900	884	0·95	$1{\cdot}105 \times 10^{-2}$	$0{\cdot}57 \times 10^{-4}$	0·368	0·25
14	2480	18,900	884	0·95	$2{\cdot}16 \times 10^{-2}$	$0{\cdot}28 \times 10^{-4}$	0·294	0·20
15	2480	18,900	884	0·95	$1{\cdot}88 \times 10^{-2}$	$0{\cdot}36 \times 10^{-4}$	0·314	0·21
16	2480	32,000	884	1·7	$1{\cdot}555 \times 10^{-2}$	$1{\cdot}13 \times 10^{-4}$	0·397	0·27
17	2550	10,300	908	0·59	$2{\cdot}13 \times 10^{-2}$	$1{\cdot}39 \times 10^{-4}$	0·382	0·205
18	2550	14,300	908	0·79	$2{\cdot}30 \times 10^{-2}$	$0{\cdot}50 \times 10^{-4}$	0·318	0·195
19	2550	14,300	908	0·79	$0{\cdot}61 \times 10^{-2}$	$0{\cdot}225 \times 10^{-4}$	0·347	0·21
20	2550	14,300	908	0·79	$1{\cdot}59 \times 10^{-2}$	$0{\cdot}945 \times 10^{-4}$	0·415	0·25
21	2960	10,400	1055	0·84	$0{\cdot}29 \times 10^{-2}$	$0{\cdot}43 \times 10^{-4}$	0·462	0·27
22	2960	10,400	1055	0·84	$0{\cdot}46 \times 10^{-2}$	$0{\cdot}605 \times 10^{-4}$	0·452	0·265
23	2960	10,400	1055	0·84	$0{\cdot}61 \times 10^{-2}$	$0{\cdot}80 \times 10^{-4}$	0·448	0·265
24	2960	10,400	1055	0·84	$0{\cdot}635 \times 10^{-2}$	$0{\cdot}475 \times 10^{-4}$	0·399	0·235
25	3380	5800	1205	0·95	$9{\cdot}65 \times 10^{-2}$	$6{\cdot}40 \times 10^{-4}$	0·385	0·225
26	3380	5800	1205	0·95	$15{\cdot}4 \times 10^{-2}$	$6{\cdot}60 \times 10^{-4}$	0·357	0·21
27	3380	5800	1205	0·95	$21{\cdot}8 \times 10^{-2}$	$11{\cdot}0 \times 10^{-4}$	0·367	0·215
28	3380	5800	1205	0·95	$28{\cdot}0 \times 10^{-2}$	$12{\cdot}4 \times 10^{-4}$	0·357	0·21
29	3380	5800	1205	0·95	$32{\cdot}3 \times 10^{-2}$	$23{\cdot}1 \times 10^{-4}$	0·394	0·23

This set and other reported sets of data (see Table 2) were used, with

$$D > 0{\cdot}15\ m$$

$$\mathscr{L}/D > 1$$

$$D/D_p \geqslant 8$$

The restrictions of packing height and column diameter were introduced in order to eliminate wall- and end-effects as much as possible; it is noted that thus only uncorrected data were taken, except where otherwise stated.

The first step was to find the exponent of the modified Reynolds number. In the case of Raschig-rings, it was found that the value was $(-0{\cdot}44)$, as is shown in Fig. 4.

The exponent of the loading number was evaluated by plotting $H_G(\mathrm{Re}')^{-0.44}$ vs. Λ for each set of data. It was found that the most probable exponent was $(-0{\cdot}39)$; some examples are given in Fig. 5, whereas a more thorough account of the calculations for the 1-in. Raschig-rings is given in Appendix 1. The dependency on column diameter and packing height is shown in the Figs. 6 and 7 respectively.

Combination of the various factors yields

Raschig-rings

$$\left(\frac{H_G S}{\varepsilon}\right) = [(\mathrm{Sc}^{0.5}(\mathrm{Re}')^{0.44}][F(\Lambda)^{-0.39}] \times \times \left[\left(\frac{D}{D_p}\right)^{0.65}\left(\frac{\mathscr{L}}{D_p}\right)^{0.195}\right] \quad (15a)$$

Berl-saddles

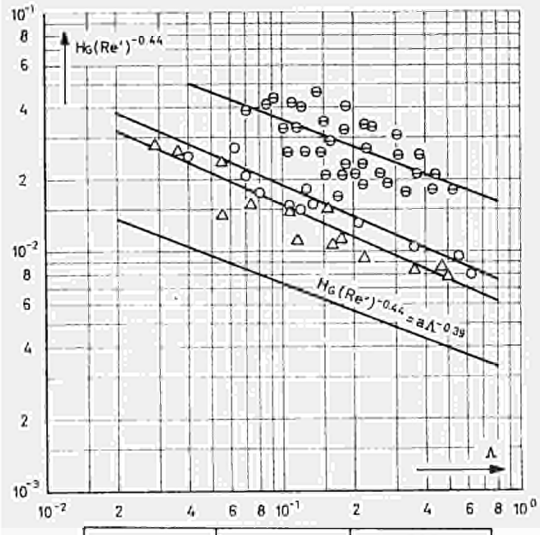
$$\left(\frac{H_G S}{\varepsilon}\right) = [(\mathrm{Sc})^{0.5}(\mathrm{Re}')^{0.77}][F(\Lambda)^{-0.45}] \times \times \left[\left(\frac{D}{D_p}\right)^{0.28}\left(\frac{\mathscr{L}}{D_p}\right)^{0.195}\right] \quad (15b)$$

The values of the factor "F" are given in Table 2, whereas in Fig. 8 these values are given as a function of the modified Weber–Froude number, making it possible to extend the correlation to other liquids.

Table 2. Data and conditions for the general correlation on gas-phase controlled mass transfer. (In all cases the carrier gas was air, the total pressure 1 atm and the temperature ambient. If no solute is given, the operation was evaporation of the liquid in air)

Packing					*Column*		*System*					
Shape	*Size*	S (m^2/m^3)	ε	D_p ($m \times 10^2$)	D (*m*)	$\mathscr{L}$ (m)	*Liquid*	*Solute*	*No. points*	$F \pm s(F)$ (%)	We′	*Reference*
Raschig-rings	$\frac{3}{8}$-in.	440	0·595	0·89	0·15	1·32	Water	Acetone	35	0·53 ± 21	11	[23]
	$\frac{1}{2}$-in.	400	0·64	1·20	0·46	0·43	Water	Ammonia	72	0·50 ± 17	19·5	[5]
					0·15	0·90	Water	Methanol				[24]
					0·15	0·56	Water	Acetone				[24]
					0·15	1·40	Water	Acetone				[23]
	$\frac{5}{8}$-in.	328	0·68	1·45	0·09	0·13	Methanol*	–	5	0·19 ± 1	60	[31]
					0·09	0·13	Benzene*	–	5	0·15 ± 3	64	[31]
					0·09	0·13	Toluene*	–	5	0·15 ± 3	64	[31]
	15 mm	310	0·69	1·40	0·25	0·32	Water	–	24	0·28 ± 22	26·5	[13]
	$\frac{3}{4}$-in.	235	0·73	1·62	0·30	1·94	5 wt.% NaOH†	Iodine	61	0·24 ± 18	38	This work
					0·15	1·38	Water	Acetone				[23]
	1-in.	190	0·73	2·20	0·46	0·65	Water	Ammonia	238	0·15 ± 21	65	[5]
					0·25	0·41	Water	Ammonia				[25]
					0·30	0·61	Water	Ammonia				[26]
					0·30	1·22	Water	Ammonia				[27]
					0·30	0·61	Water	Acetone				[26]
					0·437‡	0·61	Water	Ethanol				[6]
					0·30	0·61	Water	Ethanol				[26]
					0·30	0·61	Water	Methanol				[26]
					0·30	5·94	Water	SO_2				[28]
					0·25	0·30	Water	–				[29]
					0·25	0·32	Water	–				[13]
					0·25	0·10	Methanol*	–	15	0·13 ± 12	170	[29]
					0·25	0·10	Benzene*	–	15	0·11 ± 11	145	[29]
					0·25	0·10	Ethyl-n-butyrate*	–	15	0·10 ± 9	175	[29]
	$1\frac{1}{4}$-in.	148	0·78	2·74	0·25	1·14	Water	Acetone	35	0·20 ± 11	98	[23]
	35-mm	135	0·7	3·2	0·25	0·32	Water	–	29	0·11 ± 17	138	[13]
	$1\frac{1}{2}$-in.	115	0·68	3·56	0·46	0·64	Water	Ammonia	16	0·11 ± 25	170	[5]
					0·30	1·22	Water	Ammonia				[27]
	2-in.	92	0·74	4·45	0·46	0·60	Water	Ammonia	12	0·10 ± 10	265	[5]
Berl-saddles	$\frac{1}{2}$-in.	463	0·63	1·13	0·46	0·52	Water	Ammonia	11	0·15 ± 17	17	[5]
	1-in.	250	0·69	1·93	0·46	0·56	Water	Ammonia	52	0·0475 ± 30	50	[5]
					0·30	3·05	Water	Acetone				[24]
					0.21	1·73	Water	Acetone				[30]
	$1\frac{1}{2}$-in.	144	0·75	2·8	0·46	0·64	Water	Ammonia	12	0·022 ± 7	105	[5]

* Data used only for the verification of the introduction of the modified Weber–Froude number.
† Considered as water.
‡ Equivalent diameter of the square tower used.



SYMBOL	SIZE	REFERENCE
⊖	3/8"	(23)
○	1"	(26)
△	2"	(5)

FIG. 5. Evaluation of the loading-number exponent for Raschig-rings.

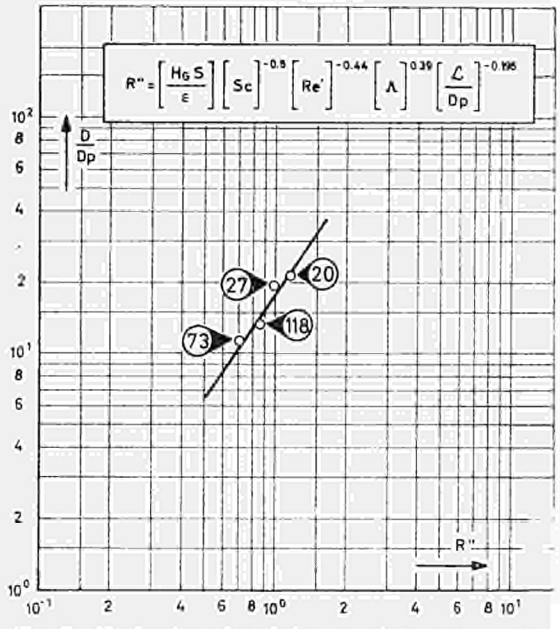


FIG. 7. Evaluation of the influence of the column diameter D on the H_G values, valid for 1-in. Raschig-rings.

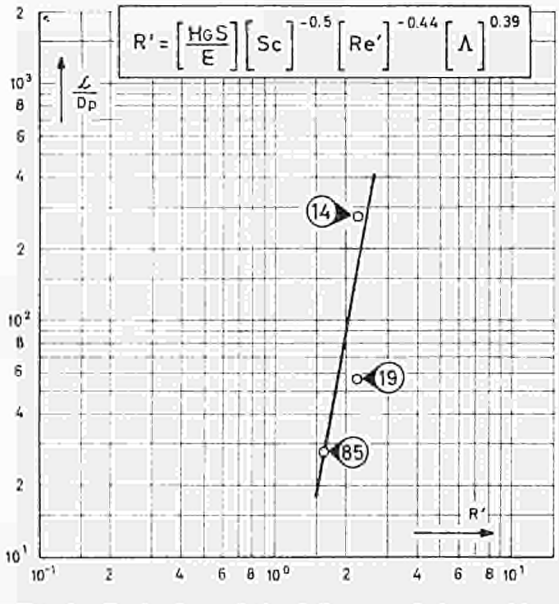
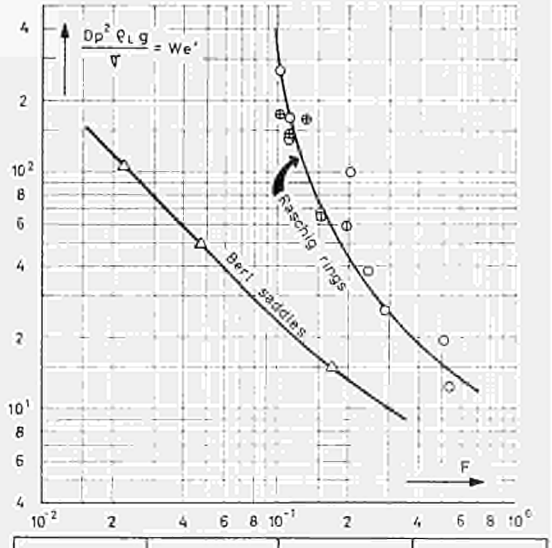


FIG. 6. Evaluation of the influence of the packing height $\mathcal{L}$ on the H_G values at a constant column diameter D, valid for 1-in. Raschig-rings at $D = 0{\cdot}3$ m. Each point represents the average value of the number of data given next to it.



PACKING	SYMBOL	LIQUID	REFERENCE
Raschig rings	⊛	Various	(29)
Raschig rings	⊙	Various	(31)
Raschig rings	○	Water	Various
Berl saddles	△	Water	Various

FIG. 8. Values of F (equations 15) vs. the modified Weber–Froude number (We').

3.2.3. *Extension to other liquids than water.* For the verification of the introduction of the modified Weber–Froude number, only two groups of data were available, all obtained with small columns not conforming to the limits mentioned before, i.e. $\mathscr{L}/D > 1$ and $D > 0{\cdot}15$ m. Data of SUROSKY and DODGE [29] and of MEHTA and PAREKH [31] were therefore corrected with an end-effect of 5 cm of packing height according to SUROSKY and DODGE [29].

The unusual small standard deviation $s(F)$ obtained with the Mehta and Parekh data is caused by the fact that here five points of each average line, as given in Ref. [31], were employed.

Since only comparable data for 1-in. Raschig-rings were available, it is noted that confirmed variation in We′ attributable to variation of the surface tension is about a factor 3 (see Table 3).

Table 3. Liquid physical properties and Weber–Froude number We′ *for 1-in. Raschig-rings at ambient temperatures*

Liquid	σ (kg/hr^2 $\times 10^{-5}$)	γ_L (kg/m^3 $\times 10^{-3}$)	We′
Water	9·4	1·0	65
Benzene	3·8	0·88	145
Methanol	2·9	0·79	170
Ethyl-n-butyrate	3·1	0·88	175

Awaiting further experimental confirmation of the introduction of We′, it is believed that the presentation of Fig. 8 can be maintained, since this is essentially the same for an ordinate equalling simply D_p or We′ for a given liquid. The latter is preferable since it gives a dimensionless presentation. For the few available data, however, the agreement between data for the various liquids is satisfactory, which shows that the introduction of the Weber–Froude number might offer the possibility to incorporate the liquid physical properties into a general correlation on gas-phase controlled mass transfer.

3.2.4. *Extension to flow rates above the loading point.* Above the loading point, both wetted surface and porosity of the packed bed change considerably, owing to an increase of the liquid hold-up. The net effect is that H_G values are higher than as would follow from equations (15).

If equation (15a) is presented as follows:

$$\frac{(H_G S/\varepsilon)(\mathrm{Sc})^{-0.5}(\mathrm{Re}')^{-0.44}(\Lambda)^{0.39}}{(D/D_p)^{0.65}(\mathscr{L}/D_p)^{0.195}} = R\Lambda^{0.39} = F \tag{15c}$$

a graph of R/F vs. Λ gives an indication of the values of H_G above the loading point (see Fig. 9). Data for $\Lambda > 1$ were taken from various sources for $\frac{1}{2}$–1-in. Raschig-rings. The general trend is that H_G values at $\Lambda > 1$ are a factor 1·2–1·8 higher than follows from equation (15a) and Fig. 8.

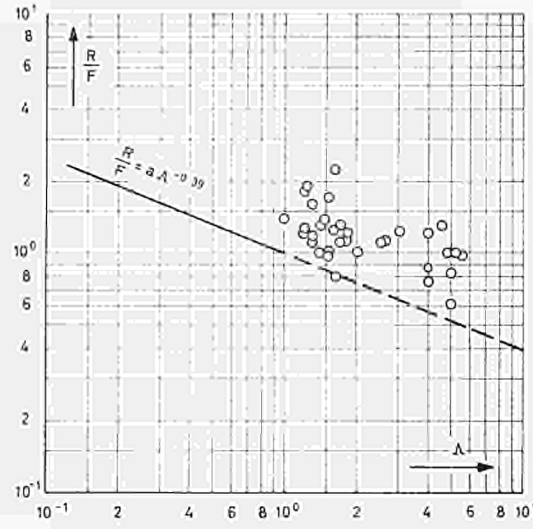


FIG. 9. Extension of the equations (15) for $\Lambda > 1$, according to equation (15c).

4. DISCUSSION

The assumption that any mass-transfer correlation should be the product and not for instance the sum, of several dimensionless groups, is purely arbitrary. It seems extremely difficult to find a way to correlate the large number of variables without the help of the logarithmic linearity that can be found often between several variables. Also here the assumption of logarithmic linearity is taken as the basis for the calculations. It is especially doubtful whether the assumption that the exponent of the Reynolds number is a constant throughout the whole region of investigation is true. This may be the reason that this exponent varies often from one correlation to another.

An attempt has been made to obtain a clear and straightforward representation of all the groups and variables to be put into a mass-transfer correlation, by arranging them as follows:
(mass-transfer group) = (gas group) × (liquid group) × (column-dimensions group).

Of all the factors put into this arrangement, only the influence of the Schmidt number was not verified. However, its exponent of −0·5 is of minor importance in view of the small variations of the Schmidt number for different gas mixtures.

No definitive conclusion can be drawn as to the correctness of the introduction of the modified Weber–Froude number. The available data were obtained with small columns, whereby erroneous effects can be important. However, as can be seen from Fig. 8, the agreement between data for different liquids is fair; besides this, it follows that the greater the modified Weber–Froude number is, the easier the dispersion of the liquid over the packing surface and the smaller the value of F will be. In other words, the mass transfer is improved.

The introduction of the column-dimensions group seems to be correct. Indeed, it is found that Berl saddles have a smaller exponent of the diameter term than have Raschig-rings. This is in accordance with the well known fact that Berl-saddles show a better liquid distribution and have a smaller wall effect than Raschig-rings. The same applies for the influence of the loading number, albeit that the difference is small.

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NOTATION

D	Column diameter	m
D_p	Equivalent spherical diameter of the packing	m
$\mathscr{D}$	Diffusion coefficient of the solute in air	m²/hr
f	Hold-up correction factor in equation (9)	
$f(—)$	Function of (—)	
F	Correction factor in equation (15), function of the modified Weber–Frounde number	
Fr	Modified Froude number, $V_L^2/D_p g$.	
G	Gas flow rate	kg/hr m²
g	Gravitational constant	m/sec² or m/hr²
H_G	Height of a gas-film transfer unit	m
H_{OG}	Height of an over-all gas-film transfer unit	m
K_G	Over-all gas transfer coefficient	kg mol/hr m² atm
k_G	Individual gas-film transfer coefficient	kg/hr m² atm
L	Liquid flow rate	kg/hr m²
$\mathscr{L}$	Packed height	m
ln(—)	Napierian logarithm	
log(—)	Briggian logarithm	
M	Mean molecular weight gas phase	kg/kgmol
N_{OG}	Number of over-all gas-phase transfer units	
P	Log mean partial pressure non-diffusing gas	atm
ΔP	Pressure drop	cm of water/m
R	Group containing all variables but Λ, equation (15a)	
Re′	Modified Reynolds number, $D_p G/\eta\varepsilon$	
S	Maximum wettable surface of packing	m²/m³
Sc	Gas Schmidt number, $\rho_G \mathscr{D}$	
S_e	Effective wetted surface of packing	m²/m³
$s(F)$	Square root of the variance of F or standard deviation of the total population of F data for each packing size	
$\bar{v}$	Relative velocity both phases	m/sec or m/hr
V_L	Liquid velocity	m/sec
w	Correction factor in equation (7)	
We	Modified Weber number, $D_p \rho_L V_L^2/\sigma$	
We′	Modified Weber–Froude number, $D_p^2 \rho_L g/\sigma$	
$y_{e,0}$	Concentration soluble gas in exit-inlet gas phase	
y^*	Concentration soluble gas at interphase	mg/m³
$(\Delta y)_{em}$	Log mean of y_e and y_0	
Γ	Wetting rate	kg/hr m
ε	Void fraction in packed bed	
η	Dynamic viscosity gas phase	kg/hr m
Λ	Loading number	
ρ_G	Density gas phase	kg/m³
ρ_L	Density liquid phase	kg/m³
σ	Surface tension liquid phase	kg/hr²
ψ	Flood factor in equation (9)	

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APPENDIX I. STATISTICAL TREATMENT OF THE 1-IN. RASCHIG-RINGS DATA

The basis of the development of the correlation presented before was formed by the 1-in Raschig-rings data, although other data were also used, e.g. see Figs. 4 and 5.

In order to check the obtained correlation, the 1-in. Raschig-rings data were analysed with an electronic computer. The following equation was put in:

$$\log R_i = a(\log \Lambda) + \log F \qquad (A.1)$$

derived from equation (15a):

$$R_i = \left(\frac{H_G S}{\varepsilon}\right)(\mathrm{Sc})^{-0.5}(\mathrm{Re}')^{-0.44}\left(\frac{D}{D_p}\right)^{-0.65}\left(\frac{\mathscr{L}}{D_p}\right)^{-0.195} = F\Lambda^a \qquad (A.2)$$

From literature twelve sets of data were available with a total of 261 points. By analysing each set separately it appeared that the data of OTHMER and SCHEIBEL [32] were not in accordance with the others (see Table A.1) and so they were abandoned.

The results obtained with the remaining eleven sets were

Number of points, $n = 238$
$a = -0{\cdot}39$, $\sigma(a) = 0{\cdot}015$
$\log F = -0{\cdot}824$, $\sigma(\log F) = 0{\cdot}018$
Coefficient of correlation, $r = 0{\cdot}953$.

The average individual values of F are given in Table A.1.

In order to calculate $\sigma(\log R_i)$, $\sigma(R_i)$ and $\sigma(F)$ the following equations were used:

$$\sigma^2(\log R_i) = (\log \Lambda)^2\sigma^2(a) + \sigma^2(\log F) + 2r(\log \Lambda)\sigma(a)\sigma(\log F) \qquad (A.3)$$

$$\sigma^2(R_i) \simeq R_i^2\sigma^2(\log R_i)\ln^2 10 \qquad (A.4)$$

$$\sigma^2(F) \simeq F^2\sigma^2(\log F)\ln^2 10 \qquad (A.4a)$$

In Table A.2 the standard deviation, or confidence range, of the various factors are shown at a confidence level of 99 per cent.

Table A.1. *Individual values of F at* $a = -0{\cdot}39$

Solute	*F*	*Reference*
Ammonia	0·16	[5]
Ammonia	0·13	[25]
Ammonia	0·15	[26]
Ammonia	0·20	[27]
Acetone	0·24	[32]
Acetone	0·13	[26]
Ethanol	0·14	[6]
Ethanol	0·15	[26]
Methanol	0·15	[26]
SO_2	0·14	[28]
—	0·15	[29]
—	0·15	[13]

Table A.2. *Confidence ranges at the 99 per cent confidence level*

Λ	R_i	$2{\cdot}59 \times \sigma(R_i)$ (%)	$2{\cdot}59 \times \sigma(a)$ (%)	$2{\cdot}59 \times \sigma(F)$ (%)
1	0·15	10·9	for all	for all
0·5	0·224	8·3	values of Λ	values of Λ
0·1	0·37	3·4		
0·05	0·484	3·65	10·0	10·6
0·03	0·69	6·0		
0·01	0·91	8·3		

Owing to the high number of degrees of freedom, $(n-2) = 236$, the significance of the correlation is better than 99 per cent, because r^2, the fraction of the variance removed by the correlation and having here a value of 0·908, should be equal to or higher than 0·026 in order to obtain the 99 per cent significance level.

It is noted that $\sigma(F)$ differs from the values given in Table 2 because this value represents the square root of the variance of the total population of the F-values at $a = -0{\cdot}39$:

$$\sqrt{[S^2(F)]} = \sqrt{\left[\frac{1}{n-1}\sum_{i=1}^{i=238}(F_i - \bar{F})^2\right]} = 0{\cdot}031 \quad (A.5)$$

NOTATION (APPENDIX I)

a Slope of equation (A.1)
F Constant of equation (A.1)
$\bar{F}$ Average value of F
F_i Individual value of F
n Number of analysed points
r Coefficient of correlation
r^2 Fraction of variance removed by the correlation
$s(F)$ Square root of the variance of the total population of F-values at $a = -0{\cdot}39$ %
R_i Individual value of R (equation A.2) %
$\sigma(-)$ Standard deviation
For other symbols, see 793.

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